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TITLE: OPTIMAL ALLOCATION OF INSPECTION RESOURCES

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OPTIMAL ALLOCATION OF INSPECTION RESOURCES*

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Abstract

Allocation of inspection resources for international safeguards is considered as the problem of designing a complex system that is composed of individual inspection activities and that has the objective of detecting material loss. Optimization theory is applied in selecting those inspection activities that maximize a system performance measure within resource constraints. The method is applicable to a global allocation problem in which inspection resources are distributed throughout a hierarchy consisting of multiple countries, multiple facilities within each country, and multiple activities within each facility.

1. Introduction

The International Atomic Energy Agency (IAEA) annually conducts over 1700 inspections of nuclear facilities throughout the world. The primary purpose of these inspections is to prevent the proliferation of nuclear weapons by deterring and detecting diversion of nuclear materials. Most strategies for improving inspection planning now under consideration involve substantial increases in the total number of inspections as well as in inspection manpower. However, our preliminary work indicates that if political and other nontechnical objectives can be met, a global inspection plan based upon an optimized allocation of inspection activities could yield substantial improvements in detection capability within IAEA resource limitations.

This paper describes a possible new strategy for examining global safeguards inspection plans. It accounts for the differences in the fuel cycle structure, the operable safeguards agreements of each country, and the cost and effectiveness of specific safeguards activities in detecting diversion. The strategy selects inspection activities using optimization theory to maximize the IAEA objective of detecting materials loss while observing a constraint on available inspection resources.

Allocation of inspection resources to facilities can be interpreted as the process of designing a complex system whose fundamental components are the activities performed by inspectors at these facilities. The design process consists of selecting these activities so that Agency objectives are accomplished within the limits of resources available for international safeguards. The steps in this process are to:

(1) state the objectives and constraints of the global inspection allocation;
(2) identify diversion scenarios that may confront the system;
(3) define the inspection activities that are responsive to these scenarios;
(4) select a performance measure for evaluating attainment of Agency objectives;
(5) select the inspection activities that maximize the performance measure and that satisfy (1).

This procedure leads to a design that is most preferred in the sense that objective accomplishment is optimized within inspection resource constraints. This design process is sufficiently general to apply to resource allocations among multiple countries having multiple facilities.

2. Inspection Allocation Objectives

For international safeguards the objectives have been stated as

"...the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."[1]

Because the deterrent influence of international safeguards depends on political and other considerations beyond the scope of this paper, we restrict consideration to the detection objective, noting that the possibility of detection contributes to the deterrence of diversion.

The objective of diversion detection is employed in this study because its degree of accomplishment is readily quantified by the probability of detection, which leads to a convenient means of preference ordering inspection plans. However, in practice, the assurance provided by nondetection of diversion is the operative aspect of international safeguards. Indeed, the conclusion of assurance that no material has been diverted and its acceptance by the international community is the final result of virtually all IAEA inspections. Thus, our choice of diversion detection as a performance measure is only for the convenience of having a quantifiable measure that can act as a surrogate for the more subjective and difficult to quantify assurance aspect of safeguards.

3. Diversion Scenarios

A number of papers have suggested that the IAEA detection objective be considered in the

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context of diversion scenarios consisting of a sequence of actions for acquiring material, removing the material to another location, and possibly falsifying evidence of these actions, in violation of international safeguards agreements.[2-6] These actions can cause anomalies in facility operations or records that may be detected by appropriate inspection activities. For example, the clandestine removal of a fuel assembly from a storage pool creates an inconsistency between facility records and a fuel assembly count, which could be detected by an inspector. In addition, an action that is part of a diversion scenario may create an anomaly in the inspection system itself as in the case of a tampering attempt against a tamper-protected surveillance instrument.

A useful distinction between scenarios is suggested by the IAEA requirement that greater concentration of verification activity be placed on material that is more readily used in constructing nuclear weapons. This implies that in designing an inspection plan those scenarios involving more attractive material be assigned a greater level of inspection effort. A further consideration in allocating inspection effort is the level of difficulty that a divertor would encounter in implementing a scenario. These two considerations--material attractiveness and technical complexity of the scenario--can be used to develop weighting factors for scenarios that reflect the relative likelihood that a divertor would select that scenario.[5]

4. Inspection Activities

An inspection system is composed of fundamental inspection activities such as counting fuel assemblies in a storage pool, verifying facility records of fresh fuel receipts, or analyzing the records of a film camera. For IAEA safeguards, these activities have been outlined for each facility type. An activity may be characterized by a number of parameters so that a given activity might be performed in several ways, require various levels of effort, and have various levels of effectiveness in detecting anomalies. For example, verifying the integrity of fuel assemblies depends on the number of assemblies to be selected for verification and the method of verification. These activities can be implemented at several levels of effort ranging from a visual observation of a few assemblies to attributes measurements on many assemblies to confirm that they contain radioactive material. The resource allocation problem consists of selecting activities and their level of implementation so that anomalies created by diversion scenarios are adequately detected in the context of all facilities inspected.

Associated with each fundamental inspection activity is a cost in agency resources. This cost may have a number of components such as the inspector's time, the equipment used, or the time of support personnel at headquarters. Our proposed method for selecting an optimal resource allocation can consider the constraints imposed by limited resources for one or more cost components. Thus, the analyst should assign the component costs to each fundamental inspector activity and an upper limit on the total resource for each component.

5. Fuel Cycle Considerations

Differences in the relative completeness of the fuel cycle of each country can influence the inspection allocation process through the diversion scenarios and inspection activities that are appropriate in the context of each fuel cycle. In effect, the fuel cycle and the inspection agreements pertaining to it provide the ground rules for developing diversion scenarios, their associated anomalies, and the possible inspection activities. Those facets of the fuel cycle that are relevant to these issues are the presence or absence of

(1) Nonproliferation Treaty (and other related treaties) signature,
(2) unsafeguarded facilities of any sort,
(3) enrichment or reprocessing capability,
(4) indigenous mining and milling of source material,
(5) heavy water production plants
(6) fuel fabrication capability
(7) bilateral technology transfer agreements,
(8) import/export trade, and
(9) States system of accounting and control existence.

A complete definition of a diversion scenario requires knowledge of the locations, amounts, and forms of the material to be diverted; the physical paths and means for removing the material; the structure of the State's accounting system and the fuel cycle; and the opportunities for hiding evidence of diversion through manipulation of the State's accounting system or the fuel cycle. For example, in countries whose fuel cycle includes a reprocessing facility, scenarios in which spent fuel is diverted for improper use are relevant. Similarly, the choice of inspection activities depends on limitations imposed by safeguards agreements and on technical considerations such as key measurement points, material inventories and throughputs for each facility, and frequency and amount of transfers between facilities and with other States. Again, as an example, the presence of a reprocessing facility should indicate emphasis on activities to verify spent-fuel inventories.

The technical details of the fuel cycle may also be used to enhance inspection efficiency. For example, where redundant information such as shipper/receiver measurement data exists, inspection effort may be reduced by verifying only part of the data. Also, knowledge of the technical operating parameters of a facility such as the throughput provides an additional means of verifying that the State's reported data are consistent with normal operations. Ideally, the complexities of the fuel cycles of individual States could best be handled by IAEA analysts by constructing computer-based material flow models for each case. A generic model of this sort is beyond the scope of the present paper.

6. Performance Measures

The goal of the resource allocation process for IAEA inspection is to find an inspection plan that best accomplishe, Agency objectives within the resource constraints. This selection process requires that a preference ordering be placed upon all inspection design options as a means of determining which distribution of inspection effort is optimal. A performance measure is a quantitative means of developing this preference ordering. Because different performance measures will, in general, lead to different optimal inspection plans, the choice of a performance measure is a key aspect of the design process, and the measure that is chosen should be compatible with the IAEA objective of detecting diversion. Thus, a performance measure should depend on the individual detection probabilities of the fundamental inspection activities against each scenario and the relative likelihood of those scenarios.

A reasonable model for developing a performance measure at the facility level is a collection of diversion scenarios $\{S_i\}$, suitably normalized weights $\{W_i\}$ chosen to reflect the relative likelihood of the scenario's occurrence based on technical considerations, such as material attractiveness and difficulty of scenario implementation, and a set of inspection plans $\{I_j\}$ where each I_j represents a complete facility inspection plan. The performance measure is the expected value of the detection probability, which is expressed as

$$\sum_i W_i P(S_i|I_j) \quad , \qquad (1)$$

where $P(S_i|I_j)$ is the conditional probability of detecting scenario S_i given that inspection plan I_j is used. In the language of statistical decision theory, the optimal design I_{opt}, which maximizes expression (1), is called a Bayes strategy.[7]

The Bayes strategy is a reasonable one when there is confidence that the $\{W_i\}$ represent the true likelihood that each scenrio would be attempted. However, where there is uncertainty about these weights, as there must be in practice given the limited experience with actual diversions, a performance measure that gives a more uniform distribution of protection over all scenarios may be more appropriate.

A maximin performance measure is defined as

$$\max_j \min_i \quad P(S_i|I_j) \quad , \qquad (2)$$

and the optimal inspection strategy under this performance measure will have a minimum detection probability over all scenarios that is greater than the minimum for any other inspection strategy. Although this performance measure selects an optimal inspection plan providing nearly uniform protection against all scenarios, this is attained at the expense of a smaller detection probability against certain scenarios when compared with the Bayes strategy.

7. Activity Optimization Program - ODOE

We have developed a computer program to find the Optimal Distribution Of Effort for inspecting facilities, where each country has multiple facilities, and each facility has multiple diversion scenarios of interest. Our ODOE software uses Bellman's dynamic programming approach to evaluate all possible assignments of inspection activities amoung facilities and to select the optimal inspection plan.[8]

For this safeguards application, ODOE has been structured as a nested dynamic program, dealing with the allocation problem as either a one or two-level decision process. The upper level, which is actually solved second, determines optimal distributions among multiple facilities using either the Bayes or maximin performance measure. At the lower level, the program finds optimal resource distributions among activities at each particular facility. Whenever multiple scenarios are examined at a facility, ODOE can use either Bayes or maximin optimization regardless of the approach used at the upper level.

ODOE or other computerized optimization techniques[6] can easily find the optimal distribution of effort for inspection activities only if we can determine the needed data. For allocating resources within a single facility the following data may be needed:

1. The total resources available for inspections (man-years or dollars),
2. A list of diversion scenarios and the action elements that comprise each scenario,
3* The relative importance or likelihood of each scenario (scenario weighting factor),
4. A list of inspection activities with options for each activity ranging from not performing the activity to the most complete accomplishment of the activity,
5 The detection capability (probability) for each option under each diversion scenario,
6. Resource cost of each option (man-years or dollars),

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*If omitted, value is assumed to be 1.0.

7.** Facility performance measure (Bayes - maximize the weighted average detection probability under all scenarios, or maximin - maximize the detection probability under the worst scenario.

When distributing resources among several facilities, two other factors come into play as well:

1.* The relative safeguards importance of each facility (facility weighting factor).

2.** Global performance measure (maximize the weighted average detection probability, or maximize the weighted detection probability for the worst facility, as determined above.

Such data can be successfully assembled using a combination of well-established techniques. These include diversion path analysis, established procedures for setting safeguards inspection levels and estimating manpower requirements, and Delphi-type expert assessments of detection probabilities and weighting factors. However, no attempt to gather all the required data in a consistent fashion has yet been made.

8. Is Optimal Allocation Worthwhile?

Moderate improvements in inspection allocations can result in large economic or detection benefits. (Note again that political and other considerations are not treated in this paper). Inspection activities on a global basis involve over 1700 inspections and over 125 man-years annually. Generally, these inspections are targeted to achieve roughly comparable safeguards levels at facilities of the same type. Currently these levels are considered to be insufficient, therefore, the overall inspection budget is being increased rapidly. Based on current trends, the number of inspections has been optimistically projected at nearly 2600 by 1988.[9]

Under fixed resource constraints, experimental allocations with OLOB and other optimization procedures, appear to yield substantially higher performance measures than those obtained through uniform allocations (i.e., when all activities are performed at similar levels). Conversely, an optimal allocation seems to achieve the same level of safeguards detection at a substantially lower resource expenditure. Although the experiments to date have generally used hypothetical data, the overall conclusions for greatly increased effectiveness may well be correct. If so, there is an opportunity here that should be looked at more closely.

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